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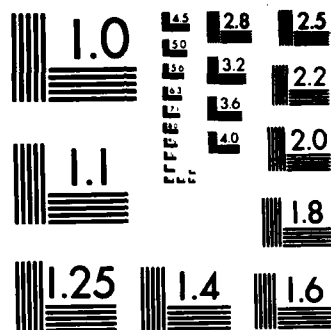
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RADIATION FROM PULSED ELECTRON BEAMS IN SPACE PLASMAS

Stanford University

K. J. Harker and P. M. Banks

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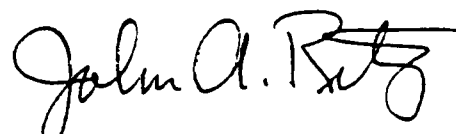
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19. ABSTRACT (Continue on reverse if necessary and identify by block number) A theoretical study has been made of the electromagnetic radiation arising from pulsed electron beams. The study assumes an electron beam which has a well organized spatial structure determined by a fixed trajectory in a magnetic field and on/off pulsing governed by the electron source. From this model the electromagnetic radiation is determined by adding coherently the radiation from each individual electron in the helical stream. This study was comprised of three parts. In the first part the number of beam pulses was assumed finite, and the beam was assumed to extend from $z = -\infty$ to $+\infty$. In the second part we assumed an infinite pulse train and took into account that the beam extends only in the half-space from $z = 0$ (the gun position) outward to $+\infty$. Formulas for the radiation as a function of ray angle, propagation angle, electron beam pulse width and separation, and beam current, voltage and pitch angle were determined. Predictions of the power radiated were made for representative examples. In the third part the theory was generalized to the near field region. <i>Keywords: electron beams, radiation, space plasmas</i>					
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I. INTRODUCTION

In this report we discuss the results of an investigation of the generation of electromagnetic waves by the process of coherent spontaneous emission arising from a pulsed electron beam moving through a magnetized plasma. The need for such an analysis arises from our desire to understand the radiative processes affecting electron beams in space plasmas. In particular, a variety of electron beam experiments have been conducted in recent years using dc and pulsed electron sources [e.g., *Winckler*, 1980; *Neupert et al.*, 1982; *Harker and Banks*, 1982]. Measurements of the electromagnetic waves generated in these experiments have been made with varied results which point to the complexity of the radiation process. Using a simple model for a propagating, pulsed electron beam, we have been able to obtain a number of predictions concerning the nature of the electromagnetic radiation pattern and the total radiated power. These results should provide an initial theoretical basis for interpreting the results of past experiments and a guide for the planning of new experiments in the future.

Our theory constructs the radiation field by adding coherently the radiation from individual electrons of a pulsed electron beam moving in a helical trajectory along a magnetic field line in a plasma, i.e., coherent spontaneous emission. Consequently, the theory for radiation from single electrons plays an important part in our work. In the development of the radiation model we draw heavily on the previous work on single-particle radiation by a number of persons, in particular, that of *Liemohn* [1965] and *McKenzie* [1967].

Basically, there are three types of radiation that can emanate from an electron beam: they are known as incoherent spontaneous emission, coherent spontaneous emission, and stimulated emission.

In incoherent spontaneous emission all the electrons radiate independently of one another, giving rise to a power proportional to the number of radiating particles. A number of authors have studied this phenomenon in relation to either natural or artificial beams [*Taylor and Shawhan*, 1974; *Etcheto and Gendrin*, 1970; *Bell*, 1968; *Singh*, 1973; *Lavergnat and Pellat*, 1979]. The general conclusion of these authors is that incoherent spontaneous emission is not strong enough to give measurable radiation from an electron beam of the type currently employed in space vehicles.

In coherent spontaneous emission, the mechanism used in this report, each particle still emits by spontaneous emission. However, the particles are constrained to travel in orbits which force all velocities in a localized region of space to be alike, and hence coherent emission occurs. This spatial velocity correlation comes from the fact that all the particles are constrained to flow along the path of a helix. However, as the beam length increases, these correlations tend to average, and we encounter the second requirement for coherent spontaneous emission, namely, beam modulation and the occurrence of fronts.

A number of workers have studied coherent spontaneous emission. *Alekhin and Karpman* [1973],

Karpman [1974], *Pellat et al.* [1973], and *Lavergnat et al.* [1974] calculated the coherent spontaneous emission from a single-beam pulse in order to explain the radiation observed in the Echo experiments [Winckler, 1980]. *Dowden* [1973] proposed the use of a system of rotating electron sources to generate coherent electromagnetic waves. His scheme does not require a pulsed beam, however, since a changing macroscopic current is achieved by means of the rotating electron sources. After theoretical analysis he calculated radiated powers of several hundred watts per ampere of electron beam current for wave frequencies in the range of 3 to 45 kHz. *Kuo et al.* [1976] extended Dowden's work with a more detailed theory which included the effects of electron velocity dispersion. For a 10-keV, 1-A electron beam, *Kuo et al.* calculated a radiated power of 1 W. *Fredricks* [1977] used beam front theory to calculate the radiation from a pulsed beam at VLF frequencies. *Lavergnat and Pellat* [1979] reexamined and updated a good amount of the previous work on coherent spontaneous emission.

In stimulated emission the beam in the presence of the background plasma becomes unstable with respect to wave growth. As opposed to spontaneous emission, emissions are stimulated by the presence of the wave itself. Since the probability of emission is directly proportional to the wave strength, the growth rate is exponential. Since this mechanism is not dependent on beam fronts, and hence on modulation, we will not discuss it here, although it is an important mechanism in its own right. There is considerable literature on stimulated emission. With respect to emission from artificial electron beams, two of the more recent articles are by *Lavergnat et al.* [1980] and *Le Queau et al.* [1980].

II. RADIATION FROM BEAMS WITH A FINITE PULSE TRAIN

Radiation from a finite pulse train was the first topic covered in detail by this project. This topic was discussed in the article "Radiation by pulsed electron beams in space plasmas" by *K. J. Harker and P. M. Banks* [1984]. The radiation from a single particle traveling through free space permeated by a magnetic field was considered first. This was later generalized to the multiple pulse case. Finally the complete theoretical treatment to describe the radiation field of a finite pulse train of electrons traveling through a space plasma was presented.

Detailed numerical studies were made of the radiation from the lower hybrid frequency up to the electron cyclotron frequency. Beam voltages considered were 100V, 1 KeV, and 10 KeV, while the beam current and pitch angle were taken as 100 ma and 30°, respectively. The 1 KeV beam voltage was taken to simulate the FPEG electron gun used in the STS-3 Space Shuttle flight.

The results from the theory show that the power radiated per unit solid angle per pulse typically lies in the vicinity of the free space value of 1 mW/sr (steradian). There is great variation with angle frequency, and for certain angles and frequencies it is not uncommon to find radiated powers per unit solid angle of the order of 1 W/sr. In addition, singularities in the power distribution

functions, up to three in number, were observed to occur; it was recommended that the conditions corresponding to these singular points should be studied in experiments, since they have the likeliest probability of detection.

It is clear from the preceding that the successful use of electron beams as radiators and antennas relies on their use at selected frequencies, observation angles, beam duty cycles, beam modulation frequencies, and pitch angles.

There are a number of factors which can degrade the results obtained. One of these is the inability to maintain a sharp front at the front and back ends of the beam. This factor has been discussed by a number of authors. Because of the importance of this effect, more work is definitely indicated to determine more accurately the role of this effect.

Related to this is the beam plasma discharge (BPD) effect. This effect has been thoroughly investigated by *Bernstein et al.* [1979]. They found that this effect takes hold whenever the beam current exceeds a threshold given empirically by the relation

$$I_c = A \frac{V^{3/2}}{B^{0.7} P L}$$

where A is a constant of proportionality, B is the magnetic field, P is the pressure, and L is the length of the beam. For the space experiments this threshold occurs at roughly $I_c/V^{3/2} = 10^{-7} A/V^{3/2}$.

For the current of 0.1 A, chosen in our work, the anode voltages of 100 and 1000 are clearly above threshold, while the anode voltage of 10,000 is exactly on threshold. Below threshold the beam acts in the fashion assumed by this paper; i.e., the beam can be described by single-particle dynamics, subject of course to effects such as space charge spreading. Above threshold, however the single-particle trajectories disappears, the beam expands, and the flow becomes more chaotic.

It is clear, then, that if our theory is to apply, then we must operate in the region below BPD threshold, or we must pulse the beam at a high enough rate that BPD cannot take hold. If the latter holds, then the theory we have described is directly applicable to the beams considered in this paper. If, on the other hand, the latter does not hold, then the experimental conditions must be changed to the condition below threshold for BPD. This could be attained by operating at currents below 0.1 A, operating at voltages above 10 kV, or using satellite orbits well above the peak of the F layer where the geomagnetic field is considerably less than 1 gauss or the pressure considerably less than 10^{-7} torr.

III. RADIATION FROM LONG PULSE TRAIN BEAMS

In the previous section we presented the results of an investigation of the generation of coherent spontaneous emission arising from a finite train of electron beam pulses moving through a magnetized medium and radiating in the frequency range between the lower hybrid and ion cyclotron

frequencies. Also, for simplicity, each pulse was assumed to traverse an unbounded path length between $-\infty$ and $+\infty$. This theory constructed the radiation field by adding coherently the radiation from individual electrons of a pulsed electron beam moving in a helical trajectory along a magnetic field line in the space plasma; i.e. coherent spontaneous emission.

Recent experiments have reported the emission of electromagnetic radiation at the modulation frequency of the electron beam when that frequency was in the VLF range. Holzworth and Koons [1981] noted the detection of emissions at 3 kHz. In experiments on STS-3 [Neupert *et al.*, 1982; Banks *et al.*, 1983 and 1984; Shawhan *et al.*, 1984] modulation of the beam at 3.1 and 4.8 kHz produced emissions at these frequencies and also at their harmonics up to the maximum observation frequency of 30 kHz. Pulse trains typically contained 32,768 pulses. Experiments with modulated beams were also carried out on the SEPAC experiment on board Spacelab-1 in November and December 1983 [Obayashi *et al.*, 1982; Taylor and Obayashi, 1984]. Holzworth and Koons [1981] also noted the detection of emissions at 3 kHz in a rocket experiment in which an electron beam was modulated at this frequency. However, because of the time delay they observed, their work will probably require a theory taking into account ion acoustic waves, a condition beyond the scope of the cold plasma wave theory presented here.

The purpose of this phase of the project was to extend our previous theory to cover these latest experiments. The details are reported in "Radiation from Long Pulse Train Electron Beams in Space Plasmas" by K. J. Harker and P. M. Banks [1985]. First, because of the relatively large number of pulses, we extended our theory to cover infinite pulse trains. Second, because most of the observations have been at frequencies in the range 1-10 kHz, we extended our numerical results to cover the region below the lower hybrid frequency. Third, we made the more realistic assumption that the beam extends only from $z = 0$ (the gun position) outward, instead of from $-\infty$ to $+\infty$. Finally, we introduced the assumption that the ability of the beam to radiate, for whatever reason, falls off exponentially with distance. The e -folding distance for this fall-off is a parameter which must be determined from more detailed theories or from experiments. We first derived general results, and then used these to specialize the theory to two cases, the long and short beam, in order to gain as much simplification as possible.

Other authors have discussed the radiation from pulsed electron beams for the special case where the beam is in parallel flow along a magnetic field axis, giving rise thereby solely to Cerenkov radiation, and sinusoidal modulation. Lavergnat and Lehner [1984] calculate the total power radiated by a beam extending from $z = 0$ to $z = vt$, while Ohnuki and Adachi [1984] calculate the far-field in cylindrical coordinates emitted by an infinitely long beam. Most recently Lavergnat, Lehner and Matthieussent [1984] have presented results for radiation from a sinusoidally modulated beam injected at an angle to the magnetic field.

Calculations to determine the radiated power based on the theory was carried out for a range of parameters. One set of computations was made for a voltage of 1000V, a current of 100 ms and a

pitch angle of 30° for comparison with the results of the STS-3 mission with the FPEG. Another set of computations were made for a voltage of 7500V, a current of 1.6A, and a pitch angle of 45° . In all cases results were presented for Cerenkov and normal and anomalous cyclotron radiation.

An important feature of the results is predicted by the factor $\sin^2(\pi\gamma b/d)$ appearing in the formula for radiated power, where b/d is the ratio of pulse on time to pulse period. If the duty cycle is $1/2$, for example, so that b/d is $1/2$, then this factor predicts that only odd harmonics will appear, while the even harmonics will not be present. If the duty cycle is $2/3$, so that $b/d = 2/3$, then this factor predicts that only harmonics corresponding to $\gamma = 1, 2, 4, 5, 7, 8, \dots$ will appear, while those corresponding to $\gamma = 3, 6, 9, \dots$ will be absent. Results from the STS-3 shuttle flight [Banks *et al.*, 1984] for modulation of the beam at 3.1 and 4.8 kHz at duty cycles of $2/3$ and $1/2$, respectively, suggest that this is the case for an appreciable fraction of cases.

Another important character of these results is their ability to indicate the possible detectability of the emissions. The most recent state of the art allows one to detect emissions above a level of $10 \mu\text{V m}^{-1}$, corresponding to a threshold power P_t of 10^{-13} W , for a bandwidth of 100 Hz. This corresponds to $10^{-15}\text{ W Hz}^{-1}$. If we make the conservative estimate that the receiver bandwidth is indeed 100 Hz, then the radiated power for all the cases studied in the paper exceed this level (10^{-13} W) and should be detectable provided $L > 2\text{ km}$ in the ionosphere.

In this work dealing with infinite pulse trains, and its predecessor [Harker and Banks, 1984] dealing with finite pulse trains, we have discussed coherent spontaneous emission from pulsed electron beams. After carrying out the mathematical simplification for the radiated power resulting from contour integrations, we are generally left with two integration variables. When the beam is infinitely long, an additional restraint is imposed in the form of the wave-particle interaction condition, which reduces the number of integration variables to one. This was the case discussed in the finite pulse train paper, where the power distribution function was chosen successively to be a function of the frequency, propagation angle, and ray vector angle.

In the present work, the beam is an unbounded pulse train. This introduces a new restraint, namely that the frequency is an integral multiple of the modulation frequency, which again reduces the number of integration variables to one. The ϕ integration in the integral is trivial and is not counted as an integration. When the beam is long, the wave-particle condition is again imposed, reducing the number of integrations to zero, and yielding a single angle for each modulation frequency. This is another way of saying that all of the power has been concentrated into radiation at a single polar angle, i.e. within those angles lying on a thin conical surface. Of course, this angle still varies with the system parameters, such as frequency and pitch angle.

IV. NEAR FIELDS IN THE VICINITY OF PULSE ELECTRON BEAMS IN SPACE

One shortcoming of the above work was that it was valid for the far-field only. This means that if the beam has a length l , then the theory is only valid for distances from the beam greater

than a factor of three or more times ¹. Since most of the measurements on electron beams in space have been taken within 10m or so of the electron beam generator, it is clear that further work was needed to be done on the near fields generated in the vicinity of pulsed electron beams.

In order to remedy this situation, a study was made at the near fields generated by a pulsed electron beam. This was reported at the 21st General Assembly of URSI in Florence, Italy August 25 - September 5, 1984 in a paper entitled "Near Fields in the Vicinity of Pulsed Electron Beams in Space" by *K.J. Harker and P.M. Banks*.

The model, as in our previous studies, assumes that the electrons follow an idealized helical path through the space plasma. The total radiation is obtained, again as above, by adding coherently the radiation from each individual electron in the helix, leading thereby to coherent spontaneous emission. The mathematical technique used consists of taking the Fourier transforms in space and time of Maxwell's equations, including the modulated beam current terms which act as the driving mechanism for the interaction. The solution is then obtained by taking the inverse transforms to obtain the electric field as a function of the spatial coordinates.

Field strengths calculated by the theory were calculated for a representative set of values of ionospheric parameters and electron beam current, voltage, and pitch angle and for a range of modulation frequencies extending from the ion to the electron cyclotron frequency.

V. PUBLICATIONS

A) Journal Articles

1. K.J. Harker and P.M. Banks, "Radiation from Pulsed Electron Beams in Space Plasmas," *Radio Science* 19, 454-470, 1984.
2. K.J. Harker and P.M. Banks, "Radiation from Long Pulse Train Electron Beams in Space Plasmas," *Planetary and Space Science* 33, 953-963, 1985.

B) Conference Papers

1. K.J. Harker and P.M. Banks, "Theory for Low Frequency Radiation from Pulsed Electron Beams," *Program and Abstracts of the National Radio Science Meeting* 11-13 January 1984, p. 72.
2. K. J. Harker, "Radiation from a Pulsed Beam in a Plasma," *Conference on Beam-Plasma Interactions in Space*, August 12-16, 1984, Rosario Resort, Eastsound, Washington.
3. K. J. Harker and P. M. Banks, "Near Fields in the Vicinity of Pulsed Electron Beams in Space," *Abstracts for OS2: Active Experiments in Space Plasmas*, XXIst General Assembly of URSI, meeting held in Florence, Italy, August 28-September 5, 1984, p. 56.

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